

Chapter 9

The lifes of a star

9.1 Introduction.

When stars are plotted in the H-R diagram, the number of stars in and out of the main sequence, together with models of stellar evolution provides a description of the possible ways in which stars are born, evolve and, eventually, die. During this process the star “move about” in the HR diagram (see Fig. 9.1). Since most stars *are* in the main sequence it is reasonable to suppose that during their life most stars *stay* in the main sequence, evolving into it when they are born and out of it when they are about to die. Models of stellar evolution confirm this.

For large objects (such as stars, galaxies, etc) the one ever-present force is gravity. This is always an attractive force which tends to condense stars and such into smaller and smaller objects. There are (fortunately) other effects which, at least temporarily, can balance gravity and stop this contraction. These effects are generated by the material which makes up the star and are always associated with various kinds of pressure (which tends to enlarge objects); a familiar example is the usual gas pressure

A less known type of pressure is produced by electrons¹ when they are brought in very close contact. Under these circumstances there is a very strong repulsion between the electrons, not only because they have equal charges (and hence repel each other), but because electrons, by their very nature, detest being close to each other: they require a relatively large breathing space. This repulsion between electrons is called *degenerate electron pressure*². This effect has a quantum origin and has many interesting

For large objects the one ever-present force is gravity

Due to their dislike of being in close contact electrons produce a *degenerate electron pressure*

¹Everything is made up of atoms. Atoms consist of a very dense and small nucleus and a bunch of electrons surrounding it.

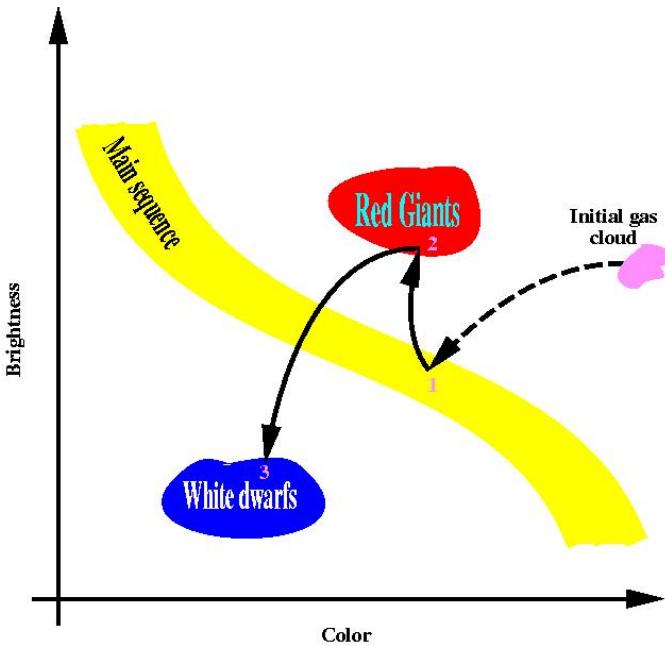


Figure 9.1: Diagram illustrating the evolution of a sun-like star. Born from a gas cloud it moves towards the main sequence (1) where it spends most of its life. After all Hydrogen is consumed in its core, the star burns Helium and becomes a red giant (2). Finally, when the Helium is consumed nuclear reactions subside and the star becomes a white dwarf (3) where it will spend its remaining (billions of) years.

consequences, to mention two, thanks to this strong dislike of electrons for occupying near-by locations, the floor supports your weight, and atoms have different chemical properties.

Electrons are not the only kinds of particles that dislike being in close contact with one another. For example, the nucleus of a Hydrogen atom, called a *proton* also exhibits this property. Finally, and this is important for stellar evolution, other particles called *neutrons* also dislike being close to each others. Neutrons have no electric charge and are slightly heavier than protons; they are also found in atomic nuclei and are, in fact, a common sight in nature. All the atomic nuclei (except for Hydrogen) are made of protons and neutrons, with the neutrons serving as buffers, for otherwise the

²This is just a peculiar name and should not be interpreted as a judgment on the moral character of the electrons.

electric repulsion of the protons would split the nuclei instantly. When close to each other neutrons produce a *degenerate neutron pressure* and protons a *degenerate proton pressure* (see Fig 9.2).

Neutrons in close contact also produce a *degenerate neutron pressure*

Protons in close contact produce a *degenerate proton pressure*

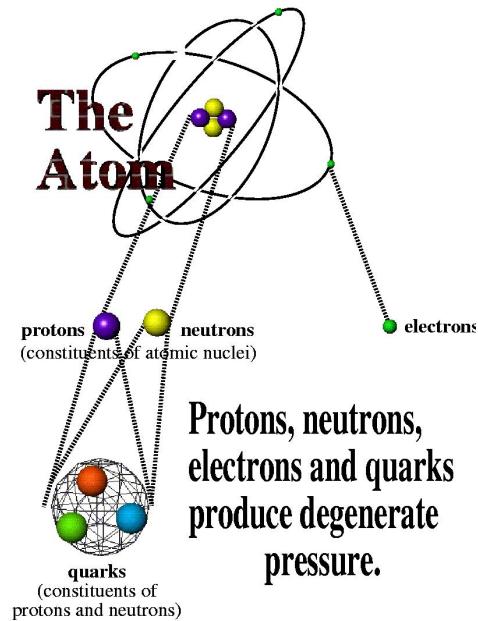


Figure 9.2: List of the most important particles which generate a degenerate pressure when in close contact. Also in the picture, the places where these particles are most commonly found.

The various stages of stellar evolution are classified according to the origin of the pressure which counterbalances gravity's pull. For most stars a balance is reached in the final stages of the star's life; there are some objects, however, for which gravity's pull overwhelms all repulsion in the stellar material, such objects are called *black holes*.

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The mass of the star largely determines its history, light stars (such as our Sun) will end in a rather benign configuration called a *White Dwarf*; heavier stars (with masses below 3-4 solar masses but larger than one solar mass) end as *neutron stars* after some spectacular pyrotechnics. Very massive stars end their lives as black holes. This will be detailed below, but before we need to understand what makes stars tick.

9.2 Stellar Power

The main power source for all stars is furnished by nuclear reactions. Possibly the most familiar of these reactions are the ones used in nuclear power plants; these, however, are *not* the ones or relevance in stellar processes. The relevant reactions present inside stars go under the name of *nuclear fusion*.

Recall that all atoms are made of a very dense and small nucleus which is positively charged and a bunch of electrons, which are negatively charged, and which surround the nucleus. At the center of the stars temperatures are very high (at least a few million degrees Celsius); pressures are also high ³. Under these circumstances the electrons are stripped off the nuclei and float around. In this large-temperature environment both electrons and nuclei travel at very high speeds, so high that when two nuclei collide they often overcome the repulsion produced by the fact that they both have positive charge. But when the nuclei come in such close contact with each other they will “stick”. The result is a new nucleus and also *energy is released*. For example one can imagine slamming Hydrogen nuclei to produce the nucleus of a new element, Helium (see Fig. 9.3).

The result of the nuclear reaction in Fig. 9.3 is the depletion of Hydrogen in the star, the creation of Helium, and the release of energy in the form of radiation. Some of the radiation will heat the environment encouraging more nuclear reactions of the same type, but a small fraction of this energy will make its way to the star’s surface and escape into space. Knowing the equivalence of mass and energy this implies that the stars become slightly lighter through this process. For our sun the loss is of “only” 1.35×10^{14} (135 trillion) tons per year (which is only about $7 \times 10^{-12} - 7$ trillionths – of a percent of the total solar mass). The jargon is that this reaction “burns” Hydrogen and that resulting “ashes” are mainly Helium.

The main nuclear reaction in stars “burns” Hydrogen and that resulting “ashes” are mainly Helium

The above is just one of a very large number of fusion reactions but it is the most common, and is present in all stars at some stage of their lives. Other reactions are also important, I will talk about them later.

As time goes on the amount of Hydrogen drops and, eventually, there is not enough left to generate appreciable amounts of energy. There are nuclear reactions involving Helium (which is now quite abundant), but they require higher temperatures. So, when the Hydrogen is used up, the nuclear reactions turn off and the star continues to contract due to the gravitational pull. But, just as before, as the contraction proceeds, the temperature at the

³Remember that the pressure must balance gravity’s pull. A star is a very massive body, hence gravity’s pull will be very large; the pressure must then be also very large to cancel it.

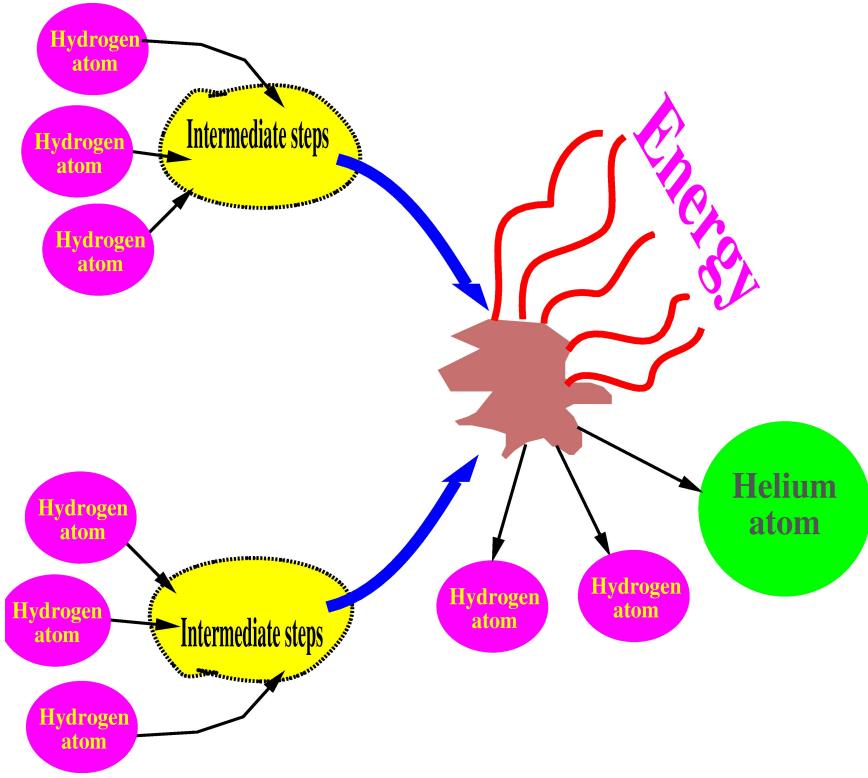


Figure 9.3: Illustration of the nuclear reactions which create Helium from Hydrogen. At very high temperatures Hydrogen atoms are slammed together, as a result a new element, Helium is created, the amount of Hydrogen is slightly depleted and energy, in the form of radiation, is released (in the “intermediate steps” some unstable nuclei are created).

core raises, eventually reaching the threshold of nuclear reactions involving Helium.

9.3 The lives of a star

9.3.1 In the beginning

It all begins with a swirling cloud of dust and debris (perhaps some old-star remnants). Gravitational attraction causes this cloud to slowly contract. As it contracts the cloud speeds up its rotation (much as an ice-skater turns faster when he/she draws her hands towards his/her body), and it heats

It all begins with a swirling cloud of dust and debris

The center of the cloud condenses into a big blob of matter

up. The cloud becomes unstable and separates into blobs, some might be ejected due to centrifugal force, others condense into planets. The center of the cloud condenses into a big blob of matter (mainly Hydrogen since this is the most abundant element in the universe). This process takes about one billion years to complete and produces a primitive planetary system: a protostar (which is very big but too cold to produce nuclear reactions) circled by protoplanets. As time goes on, the protoplanets in their orbits will “sweep-out” the remaining debris from the cloud.

Pressures and temperatures at the center are so high that nuclear reactions turn on
The main reaction occurring at this stage consume Hydrogen and produce Helium

9.3.2 A rising star

Through the evolution of the star the only force opposing the gravitational collapse is the pressure of the stuff the central blob is made of; this pressure is initially very small compared to the pull of gravity. This means that the blob will contract until pressures and temperatures at the center are so high that nuclear reactions turn on. At this point the energy release from the fusion reactions heats up the stellar material, this in its turn increases the pressure and the contraction stops. As mentioned above, the main reaction occurring at this stage consume Hydrogen and produce Helium: the star “burns” Hydrogen into Helium. This goes on for a long time: if the star is light (as our sun) it proceeds for about 10 billion years, much heavier stars use up Hydrogen much faster (for the heaviest ones it takes ‘only’ 1 million years).

When burning Helium the star becomes a *red giant*

9.3.3 A Giant appears

After the supply of Hydrogen in the core is depleted the corresponding nuclear reactions stop (there are other fusion reactions, but they can occur only at higher temperatures than the ones present at the center of the star at this stage). Then the pressure drops and the gravitational collapse proceeds. During this process the center of the star is compressed more and more, increasing the central temperature until, finally, it becomes so hot that nuclear reactions involving Helium start up: Helium atoms slam together, and, after a complicated reaction produce Carbon. When these reactions turn on the energy output is enormous, the core becomes extremely hot and radiates a very large amount of energy. This radiation pushes out the outer layers of the star, and as they are pushed out they become a bit cooler and thus look redder. The star then becomes a *red giant* a bloated result of the burning of Helium Our sun will eventually go through this process and will grow to the point that it will engulf the orbits of Mercury, Venus and,

possibly, the Earth.

9.3.4 And so it goes

What happens when the supply of Helium is used up? The story is repeated: gravitational contraction takes over and the star collapses further. Eventually other nuclear reactions become viable, power increases until the various nuclei are depleted, then contraction takes over again. In this manner the star produces, Oxygen, Silicon and, finally, Iron. this is, in fact, the way in which these elements are manufactured in nature. Every bit of Carbon in a flower's DNA, every bit of Oxygen we take in every breath, every bit of Silicon in a sandy beach was created in a star.

Stars create Oxygen, Silicon and, finally, Iron

When the core of the star turns into Iron all nuclear reactions stop, permanently. The reason is that Iron is a very stable nucleus so that if two Iron nuclei are slammed together they will only stick if energy is *supplied* (in contrast, two Hydrogen atoms stick and also release energy). When nuclear reactions stop gravitational contraction continues again and will proceed until the electrons in it are closely squashed together. As mentioned above electrons dislike being in close contact with each other and when squashed will generate a pressure which opposes gravity; whether this pressure is sufficient to stop collapse depends on how heavy the star is.

Light stars

For stars lighter than 1.4 solar masses the electron degenerate pressure will balance gravity. The star has by now contracted from its red-giant size to the size of a small planet (like Earth). The material of this star is so dense a teaspoon of it would weight 1 ton on Earth.

When this final contraction occurs there is a certain amount of overshoot and bouncing back and forth before stability is achieved; in this process all the outer layers of the star are ejected. The end result is a beautiful ring of stellar material which spreads out, at the center of which a small star, called a **white dwarf**, remains (see Fig. 9.4). White dwarfs are stable and their racy days of nuclear reactions are forever gone; they slowly radiate their remaining heat little by little and eventually become dark cinders. This is the end of a star whose mass is smaller than 1.4 times the mass of the Sun; this process is summarized in Fig. 9.5

It is interesting to note that the theory *predicts* that these objects will always be lighter than 1.4 solar masses. Observations have confirmed this. This theory is a combination of quantum mechanics and gravitation and, in

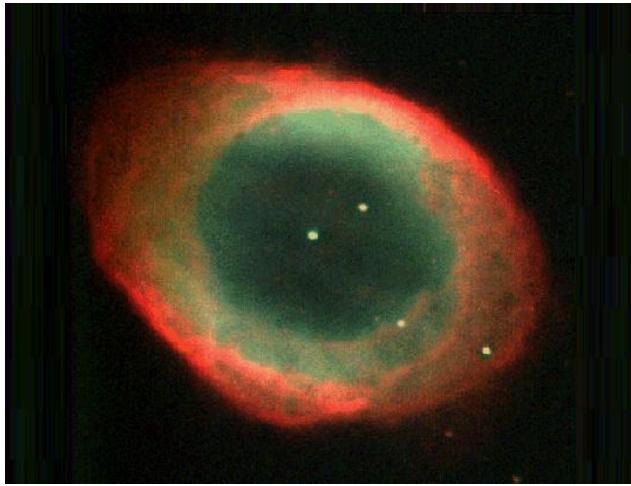


Figure 9.4: Photograph of a ring nebula. The central white dwarf has, in its last throes, expelled its outer layers appearing here as a ring surrounding the small remnant.

fact, it provided the first application of quantum physics to stellar objects.

For heavier stars the pull of gravity overcomes the degenerate electron pressure and collapse continues.

Electrons, protons and neutrons. Matter in most situations is composed of electrons, protons and neutrons. Electrons are negatively charged and weigh 9×10^{-31} kg, protons weight 1.8×10^{-27} kg and have positive charge, exactly opposite to that of the electrons. Neutrons weigh as much as protons and have no charge. Usually protons and neutrons are bound together in atomic nuclei and are surrounded by a cloud of electrons so that the whole system is neutral. If, however, matter is subjected to higher and higher pressures, eventually the atoms are crushed together to the point that the electrons can jump around from the vicinity of one nucleus to another.

If the pressure is increased still further the nuclei themselves are brought into close contact and lose their identities. At this point the protons undergo a reaction in which they absorb an electron and turn into neutrons while emitting a neutrino (yet another subatomic particle). Because of this process most of the matter turns into neutrons and neutrinos. The latter interact very seldom and just leave the system; because of this what remains is essentially an enormous number of neutrons

The life of a star lighter than 1.4 solar masses

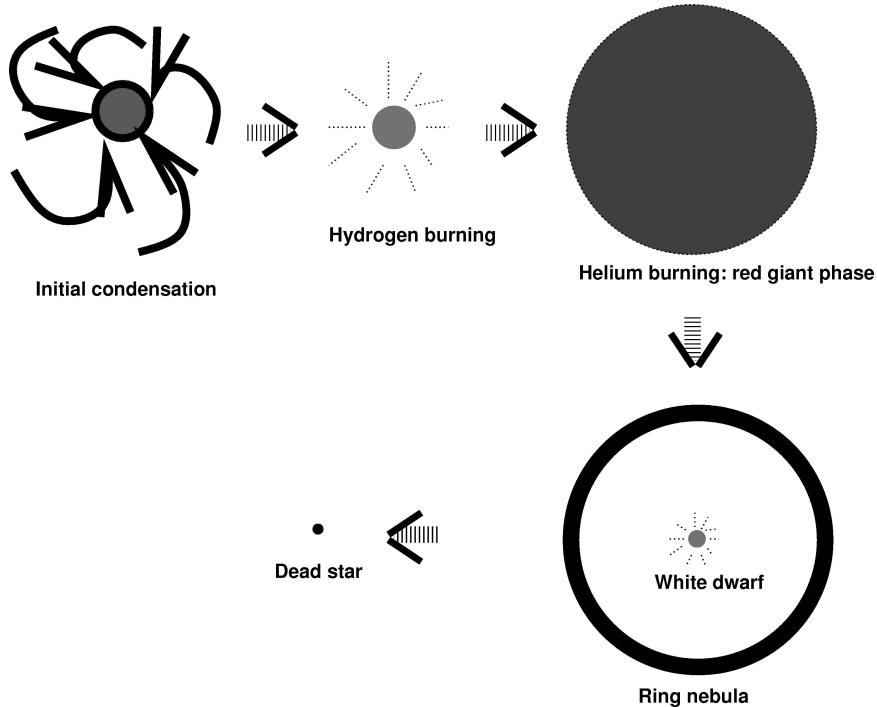


Figure 9.5: Time and life of a star of mass below 1.4 times the solar mass (less than about 3×10^{27} tons).

Medium-size stars

For stars heavier than 1.4 solar masses but lighter than about 3–4 solar masses (the calculations are still a bit uncertain), the electron pressure is not strong enough to balance gravity. The contraction then goes crushing the electrons together and braking apart the Iron nuclei into their constituents. These constituents, neutrons and protons, also detest being close to each other and, as mentioned above, produce a (degenerate) pressure which opposes gravity. For a star in the present mass range this pressure is sufficient to stop further collapse, but is effective only when the material is extremely dense which occurs only when the star has contracted to an object a few kilometers in diameter.

The contraction of these stars from their initial solar size to the size of a city is one of the most spectacular events in the heavens: a supernova. Imagine an object weighting 5×10^{27} tons (that is five thousand trillion-

trillion tons, or about 2.5 solar masses), which contracts from a size of 10^6 (one million) kilometers to about 10 kilometers, and it all happens in a fraction of a second. During collapse the amount of energy generated is fantastic, part of it goes into creating all elements heavier than Iron, part into creating neutrinos and part is transformed into light.

Radioactive elements are also created during the collapse. These elements rapidly decay, and the resulting radiation is so intense it produces a fantastic flash of light. At this point the supernova will out-shine a full galaxy of normal stars (several billion or up to a trillion of them!).

After the collapse there is a violent overshoot before equilibrium sets in, at this time all the outer layers of the star are ejected at speeds close to that of light. When this material goes through any planets around the star (if any) it vaporizes them. In the middle of this cloud the core of the original star remains, a rapidly rotating remnant, protected against further collapse by its neutron degenerate pressure.

The overshoot is so violent that the elements created will be strewn all over the region surrounding the star, part of this material will end up in dust clouds which will become stellar systems (the shock produced by the supernova material colliding with a dust cloud may initiate the formation of a stellar system); this is how the Earth acquired all elements aside from Hydrogen and Helium. Every bit of tungsten used in our light bulbs came from a supernova explosion, as did all the uranium, gold and silver. All the iron in your hemoglobin got there through a supernova explosion, otherwise it would have remained locked into the deep interior of some star.

The most famous supernova was observed by Chinese astronomers more than one thousand years ago (see Sect. ??), its remnants are what we call the Crab nebula (Fig. ??). We also met another important supernova (see Sect. ??) observed by Tycho Brahe in 1572 (Fig. 9.6). In 1987 a star in our galaxy “went” supernova, since then we have observed the ejecta from the star and the remnant of the core (Fig. 9.7). There are, of course, many known supernova remnants (see, for example, Fig. 9.9). The evolution of a middle-size star is illustrated in Fig. 9.8.

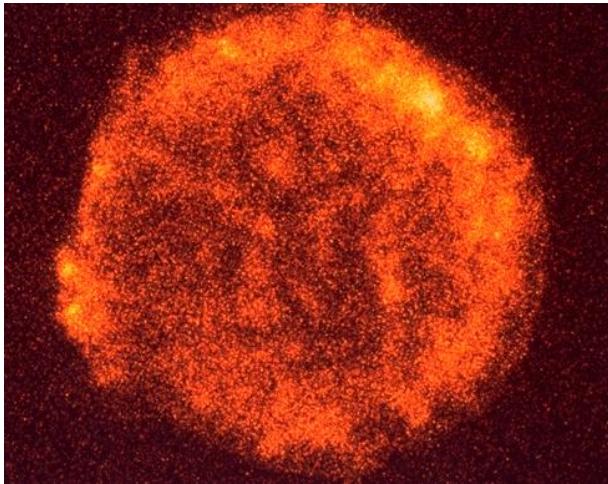


Figure 9.6: An X-ray photograph of the remnant of Tycho's supernova.

The Crab nebula. The Crab nebula in Fig. ?? is the remnant of a supernova explosion. The explosion was observed on July 4, 1054 A.D. by Chinese astronomers, and was perhaps about as bright as the Full Moon, and was visible in daylight for 23 days. It was probably also recorded by Anasazi Indian artists (in present-day New Mexico and Arizona), as findings in the Chaco Canyon National Park (NM) indicate

After gravity is balanced, and after the exterior shells are ejected the star stabilizes forever. But not without some fancy footwork: the remains of the star usually rotates very rapidly (up to 30 times per second!) and it also possesses a very large magnetic field. These two properties cause it to emit X-rays in a directional fashion, sort of an X-ray lighthouse. Whenever the X-ray beam goes through Earth we detect an X-ray pulse which is very regular since the star's rotation is regular. This is called a *pulsar*. As time goes on the rotation rate decreases and the star dies a boring *neutron star*. Neutron stars are very compact objects having radii of about 10 km (6 miles) so that their density is enormous, a teaspoon of neutron-star material would weigh about 10^{12} (one trillion) tons on the Earth's surface.

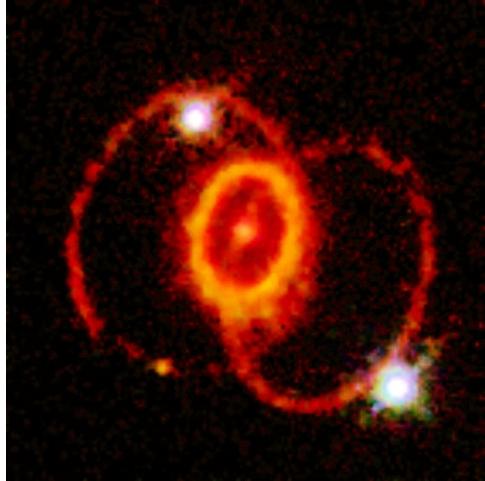


Figure 9.7: Left: a picture of the supernova 1987A remnant (the most recent supernova in our galaxy. Right: photograph of the core.).

9.3.5 The heavyweights

But what happens for stars heavier than about 3-4 solar masses? In this case the pressure from the squashed nuclei cannot stop the gravitational attraction and collapse continues. In fact no known effect can stop the collapse and it will go on and on until the star collapses to a point. This how a *black hole* is created (see Sect. ??).

For this object the gravitational force is so big that even light cannot leave its vicinity: as mentioned in section ??, if a light beam comes too close to the center of such an object, the bending effect is so severe that it spirals inwards. Light emitted from up to a certain distance will be bent back into the star. This distance defines a horizon: nothing inside the horizon can ever come out, nothing that crosses the horizon ever leaves the black hole. The more massive the black hole, the larger the horizon.

For a very massive black hole an astronaut may cross the horizon without feeling any personal discomfort, only later he realizes that he is inside a cosmic Venus fly-trap (or roach motel ⁴) out of which there is no escape.

General relativity together with our knowledge of subatomic physics guarantees that a sufficiently large star will eventually collapse to the point where a horizon appears. The manner in which such a star evolves thereafter is impossible to know since no information from within the horizon can be

⁴You check in...but you never check out

The life of a star between 1.4 and 3 solar masses.

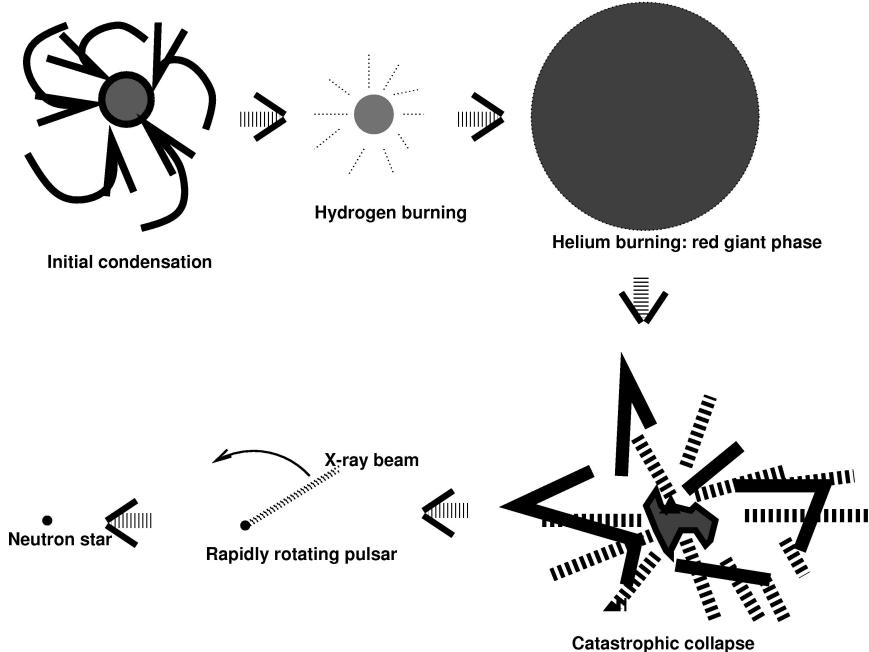


Figure 9.8: Time and life of a star of mass between 1.4 and 3–4 times the solar mass (between about 3×10^{27} and 7×10^{27} tons).

sent to the outside universe. There might be some new kind of effects which will stop the collapse of even the most massive stars, but even then the horizon *will* remain. The point is that our *present* knowledge of physics predicts the existence of black holes, even if we do not know *all* physical effects in Nature. The fact that we have several excellent black-hole candidates supports (albeit indirectly) our understanding of gravitation and physics in general.

The detection of black holes is difficult: one looks not for the object itself but for certain characteristics of the radiation emitted by matter falling into the black hole; see Fig. ???. Anything coming near the black hole will be strongly attracted to it, it will swirl into the black hole, and in the process it will heat up through friction, this very hot matter emits electromagnetic radiation in a very characteristic way and it is this pattern what the astronomers look for (see Sect. ??).

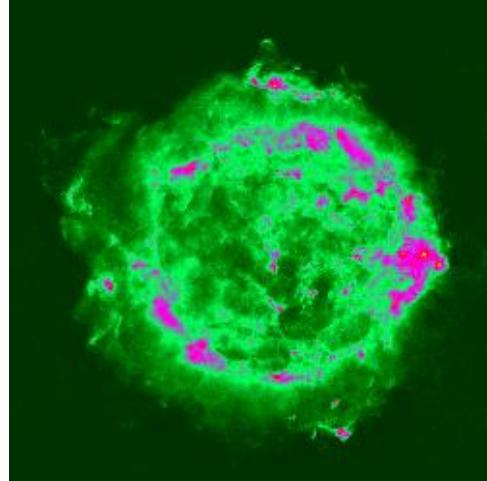


Figure 9.9: A radio picture of the Cassiopeia A nebula, a supernova remnant.

The best candidate for a black hole was, for a long time an object in the constellation Cygnus and is called Cygnus X1. Very recently (May 1995) an object with the name GRO J1655-40 in the constellation of Sgrittarius became an excellent black-hole candidate. In this object a star is accompanied by an object that emits no light, there is material falling into the companion and the X-rays from this material are unique to black-holes. Moreover, the mass of the companion can be determined to be heavier than 3.35 solar masses. The companion has then all the properties of a black hole.

Black holes are also supposed to be the engines at the center of active galactic nuclei and quasars (see Fig. 9.11). These are very distant objects which, by the mere fact of being detectable on Earth, must be immensely luminous. So much so that nuclear energy cannot be the source of that much radiation (you'd need more nuclear fuel than the amount of matter in the system). On the other hand, a black hole of several million and up to a billion solar masses can, by gulping down enough stellar material (a few suns a year) generate in the process enough energy.

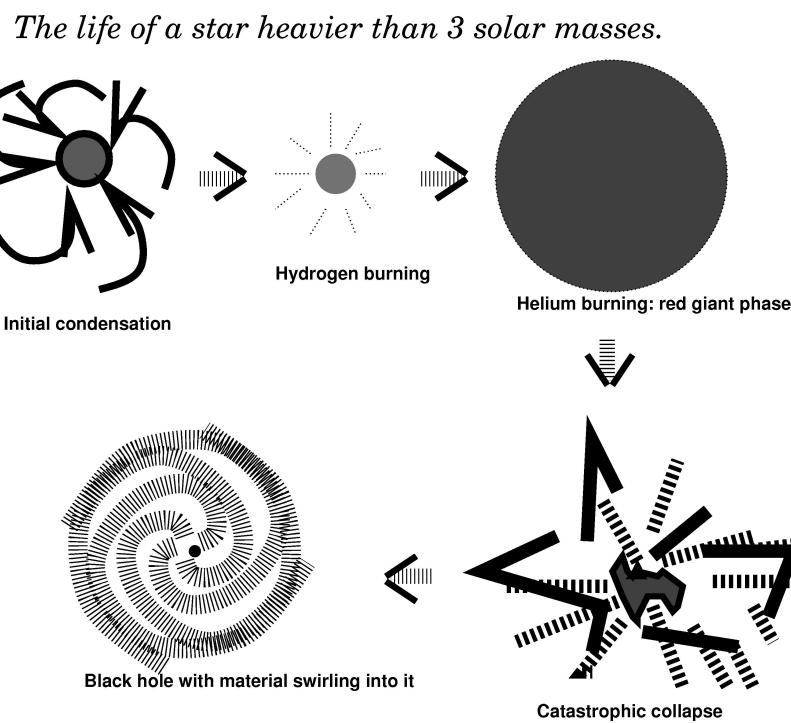


Figure 9.10: Time and life of a star of mass heavier than 4 solar masses (8×10^{27} tons).

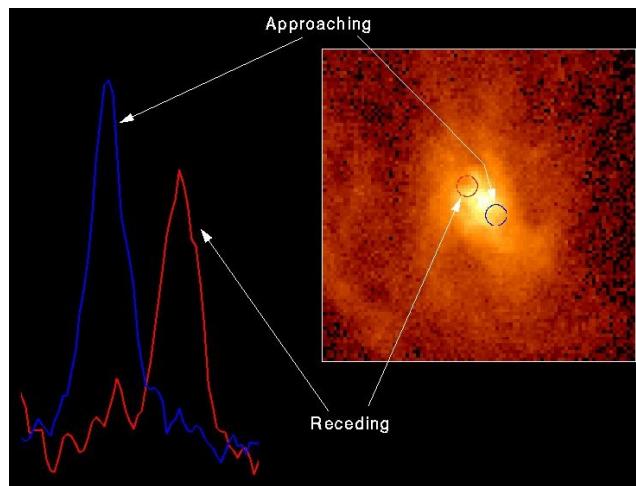


Figure 9.11: A disk of accreting matter onto a very compact object believed to be a black hole. The object at the center of M87 (located 50 million light-years away in the constellation Virgo) weights about three billion suns, but is concentrated into a space no larger than our solar system. The black hole is surrounded by a disk of matter which is being sucked into the center; as the matter falls in it radiates, and the emission from two regions are measured. Using the Doppler effect one can calculate the velocity of the material falling in; the region labeled “approaching” emits blue-shifted light, while light from the “receding” region is red-shifted. The speed of the gas is enormous: 1.2 million miles per hour (550 kilometers per second).